Proceedings of the 12th Asian Congress of Fluid Mechanics
18-21 August 2008, Daejeon, Korea

UNSTEADY RANS SIMULATION OF INCOMPRESSIBLE FLOW PAST A SYMMETRIC AEROFOIL AT HIGH ANGLES OF ATTACK

Sekhar Majumdar B. N. Rajani D.S.Kulkarni M. B.Subrahmanya

Computational & Theoretical Fluid Dynamics Division
National Aerospace Laboratories (CSIR), Bangalore
sekhar@ctfd.cmmacs.ernet.in rajani@ctfd.cmmacs.ernet.in

Key Words : Multiblock Boundary Conforming Grid, Pressure-Velocity solution strategy, Implicit RANS solver, Eddy viscosity based Turbulence Models, Unsteady Separated Flow, Vortical flow structures

ABSTRACT*: Turbulent flow past a stationary NACA0012 aerofoil at high angle of attack is analysed solving the Unsteady Reynolds Averaged Navier Stokes (URANS) equations coupled to different eddy-viscosity based turbulence models. The complex phenomena of vortex shedding for stationary aerofoil at very high angles of attack has been reasonably captured by the present method*

1. INTRODUCTION

In recent years, simulation procedures based on the numerical solution of Unsteady Reynolds Averaged Navier Stokes (URANS) equations have been accepted by the aerodynamics community as a potential research tool for analysis of massively separated flow behind two dimensional aerofoils at very high angles of attack. At high angles of attack, the flow has strong non-linearities due to unsteadiness, flow separation, viscous/inviscid, vortex/body or vortex/vortex kind of interactions and often due to laminar to turbulent transition or relaminarisation. In the URANS methodology, the governing equations for mean flow, coupled to an appropriate statistical turbulence model, are framed on the basis of phase averaging which is valid only when there exists a spectral gap between the low frequency unsteadiness of the mean flow and the internal frequencies of the fluid turbulence. The present prediction of flow pattern and of the mean aerodynamic coefficients up to an angle of attack of 90 degrees, compares reasonably well with the corresponding measurement data.

2. Mathematical Modeling

The phase-averaged Navier Stokes equations for unsteady incompressible flow in the coordinate-free form is written as follows, where μ and ρ are the fluid viscosity and density respectively; $\langle p\rangle$ and $\langle U\rangle$ are the phase-averaged pressure and velocity vector respectively; u is the fluctuating velocity vector due to turbulence and $\langle S\rangle$ is any other momentum source vector.

Momentum conservation :

$$\frac{\partial\left(\rho\langle U\rangle\right)}{\partial t}+div\left(\rho\langle U\otimes U\rangle\right)=-grad\langle p\rangle+\mu\,\nabla^2\langle U\rangle-div\left(\rho\,\langle u\otimes u\rangle\right)+\langle S\rangle \tag{1}$$

Mass conservation :
$$div\left(\rho\langle U\rangle\right)=0 \tag{2}$$

The Reynolds Stress tensor $(-\rho\langle u\otimes u\rangle)$ is computed using an appropriate eddy-viscosity based turbulence model. For the present analysis low Reynolds number version of $k-\varepsilon$ model of Chien [1], Wilcox's $k-\omega$ model [2], Menter's SST model [3], one equation model of Spalart-Allmaras (S-A) [4] and the $k-\varepsilon-\overline{v^2}-f$ model proposed by Durbin [5] popularly known as V2F are used to simulate turbulence effects in the flow computation.

2.1 Numerical Method

The present computation uses a general geometry, block structured, pressure-based implicit finite volume algorithm RANS3D, developed at the CTFD Division, NAL Bangalore to solve the unsteady turbulent incompressible flow[6-8]. Central Difference and other high order Upwind schemes have been used for spatial discretisation of the convective fluxes whereas the temporal derivatives are discretised using the second order accurate three-level fully implicit scheme. An iterative decoupled approach similar to the SIMPLE algorithm[9], modified for collocated variable arrangement [10] is adopted to avoid the checkerboard oscillations of the flow variables. The system of linear equations derived from the finite volume procedure is solved sequentially for the velocity components, pressure correction, turbulence scalars and temperature using the strongly implicit procedure of Stone [11].

3. RESULTS AND DISCUSSION

3.1 Computational Details

The preliminary investigations for flow past NACA0012 aerofoil [8,12,13] have confirmed the parameter values for which the results are more or less independent of the grid size, the location and kind of boundary condition at the far field boundaries and also of the free stream turbulence level prescribed at the farfield. A 2-block O-grid consisting of 320×100 control volumes has been employed with the far field placed at a radius of 30C and the minimum wall normal distance is maintained to be around 8×10^{-6} C, where C is the chord length of the aerofoil. The third order accurate QUICK [14] scheme for convective flux discretisation coupled to second order accurate temporal discretisation scheme with time step size $\Delta t = 0.05$ have been used for the present computations. The eddy viscosity at far field is assumed to be approximately equal to the laminar viscosity. Computations have been carried out using five different turbulence models mentioned in section 2 for each of the flow situations at different angles of attack.

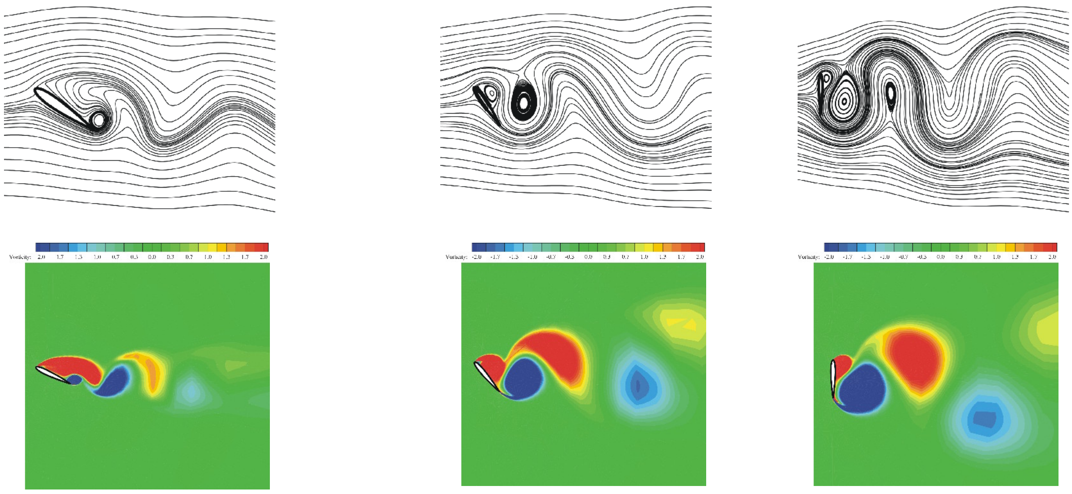
3.2 Instantaneous particle trace and vorticity contours

Fig. 1 shows the typical instantaneous particle traces and vorticity contours for three different angles of attack, computed using the S-A turbulence model and in a qualitative sense, similar flow patterns are produced by the different turbulence models used. The figures clearly show the distinct difference in the vortical structure of the wake flow as the angle of attack changes from 25^0 to 90^0. At $\alpha=25^0$, a small trailing edge vortex is shed from the suction surface of the aerofoil and negative streamwise velocity is observed almost all over the suction surface of the aerofoil. As the angle increases to 50^0, a large clockwise vortex is formed covering a large part of the suction surface indicating significant enhancement of the lift coefficient. Finally at $\alpha=90^0$, when the aerofoil behaves like a disc normal to the flow, the vortex generated on the suction surface shrinks back towards the leading edge, shedding a very large anticlockwise vortex in the near wake covering almost the full blockage area behind the aerofoil. The change of sign of the vorticity contours indicates the typical vortex street generated in the aerofoil wake consisting of the alternating vortices shed from the aerofoil suction surface. The width of the vortex street is also clearly observed to increase as the angle of attack increases from 25^0 to 90^0.

3.3 Temporal evolution of the aerodynamic coefficients

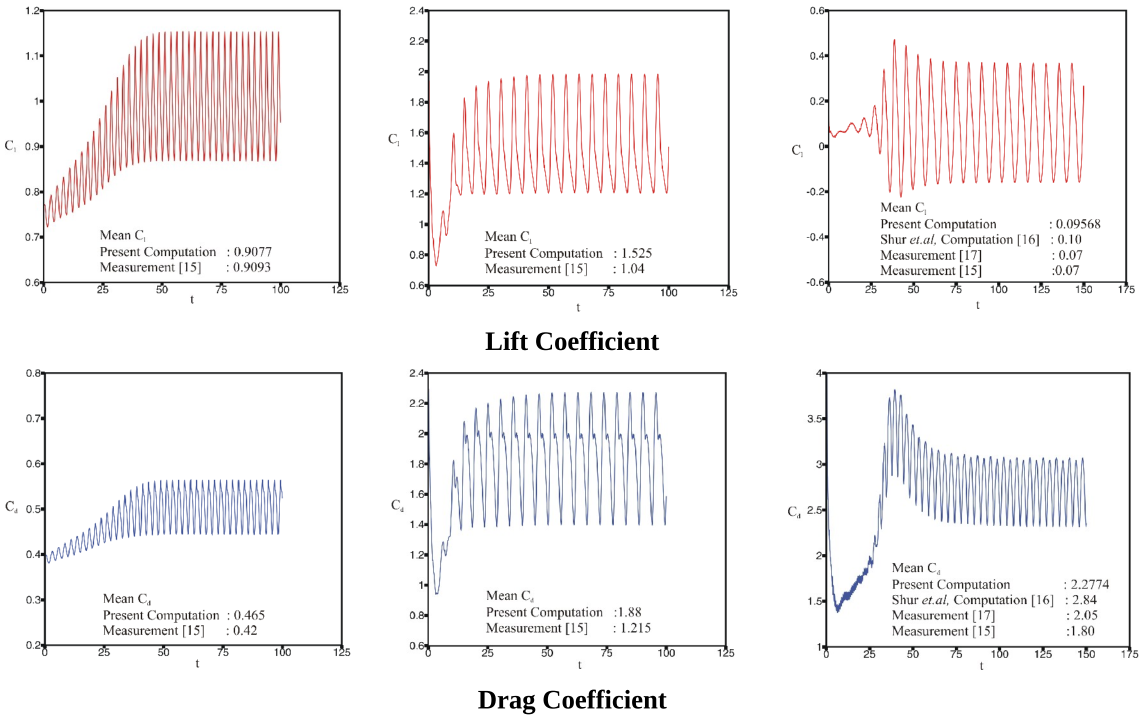
The instantaneous aerodynamic coefficients are calculated from the integration of the tangential wall shear stresses and the wall-normal pressure forces over the whole aerofoil surface. The temporal evolution of the lift and the drag coefficients of the aerofoil are shown in Fig. 2 for three different angles of attack. The corresponding measurement data on mean aerodynamic coefficients and the computed Strouhal number are also shown in the same figure. The mean values of the lift and drag coefficients computed using S-A turbulence model for all the three angles of attack are found to be in reasonable agreement with the corresponding measurement data reported by various researchers[15,17]. Table 1 shows the sensitivity of the turbulence model on the computed mean aerodynamic coefficients and the

Strouhal number at the extreme case of $\alpha=90^0$ and significant variation is observed in both computation results as well as in the measurement data reported by different researchers.



$\alpha = 25^o$ $\alpha = 50^o$ $\alpha = 90^o$

Fig. 1 Instantaneous particle traces and vorticity contours for flow past NACA0012 aerofoil at different angles of attack (computation using S-A turbulence model)



$\alpha = 25^o$ $\alpha = 50^o$ $\alpha = 90^o$

Fig. 2 Temporal evolution of aerodynamic coefficients for flow past NACA0012 aerofoil at different angles of attack (computation using S-A turbulence model)

Table 1 Mean Aerodynamic coefficients and Strouhal number for NACA0012 at α = 90^0

Aerodynamic coefficients	Present Computation					Shur *et.al* [16] computation		Measurement	
	k-ε Chien	k-ω	SST	SA	V2F	2D	3D	Hoerner [17]	Sheldahl *et. al*[15]
Lift, C_l	0.060	0.077	0.053	0.096	0.063	0.10	0.11	0.07	0.07
Drag, C_d	2.741	2.977	3.155	2.775	2.753	2.84	2.54	2.05	1.80
Strouhal Number	0.098	0.117	0.120	0.117	0.117				

CONCLUDING REMARKS

The present two-dimensional unsteady RANS predictions at very high angles of attack are found to be in reasonable agreement with corresponding measurement data on the mean aerodynamic coefficients. However the discrepancies and the sensitivity to the turbulence models may be attributed mainly to the inherent inadequacy of all the eddy viscosity based turbulence models to capture flow separation and transition. Work is in progress on Large Eddy Simulation for more accurate prediction of unsteady separated flows.

ACKNOWLEDGMENTS

The authors wish to thank the Director NAL, Bangalore for kind permission to publish this paper

REFERENCES

[1] Chien KY. *AIAA Journal*, 1982, 20(1), 33-38

[2] Wilcox DC. ***Turbulence Modelling for CFD*, DCW Industries.** Inc., California, 1993.

[3] Mentor FR. *AIAA Journal*, 1994, 32(8), 1598-1605

[4] Spalart PR and Allmaras SR . *AIAA Paper 92-0439, 1992*

[5] Durbin PA and Reif BAP. ***Statistical theory & modelling for turbulent flows***, John Wiley & Sons Ltd., 2001

[6] Majumdar S and Rodi W. and Zhu J. *J. of Fluid Engg., ASME*, 1992, 496-503

[7] Majumdar S and Rajani BN and Kulkarni DS and Mohan S. *Proc. Seminar on State of the Art and Future Trends of CFD at NAL*, NAL SP 0301, 2003, 31-48

[8] Rajani BN and Govindraju L and Majumdar S. *Proc. 7th ACFD Conf.*, Bangalore, November 2007 399–411

[9] Patankar SV and Spalding DB. *Int. J. of Heat & Mass Transfer*, 1972, 15, 1787-1806

[10] Majumdar S. *Numerical Heat Transfer*, 1988, 13, 125-132

[11] Stone HL. *SIAM J. of Numerical Analysis*, 1968, 5, 530-538

[12] Kulkarni DS and Rajani BN and Majumdar S. *NAL PD CF 0212, 2002*

[13] Govindaraju L. M.E. Dissertation, UVCE, Bangalore University, 2005

[14] Leonard BP. *Computer Methods in App. Mech. And Engg.*, 1979, 19, 59-98

[15] Sheldahl RE and Klimas PC. *SAND80-2114*, Sandia National Laboratories, New Mexico, 1981

[16] Shur ML and Spalart PR and Squires KD and Strelets M and Travin A. *AIAA J.*, 2005, 43(6), 1230-1242

[17] Hoerner SF. Fluid-Dynamic Drag, Midland Park, NJ, 1958